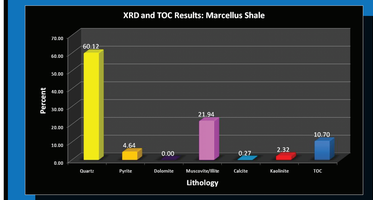
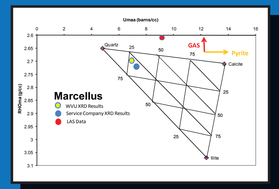
# MINERALOGICAL ANLAYSIS

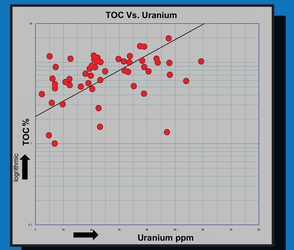



Example of X-Ray Diffraction (XRD) and Total Organic Carbon (TOC) results for a typical Marcellus sample in the study area. In the study area TOC can range from 2-16% This sample has a high amount of quartz (60%) and fairly low amount of clay (21%), which is characteristic of the 36 Marcellus Shale samples throughout the study area. Also, it is important to identify that there is a significant amount of pyrite. This sample has about 4% Pyrite but the samples can range from 4-10%.

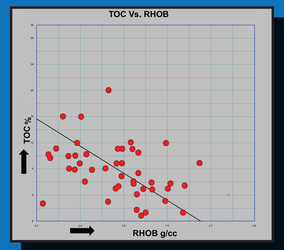



RHOma Umaa plot for a single foot of the Marcellus Shale compared to core analysis. The blue and yellow circles are the XRD results and the red circle is the LAS data. It shows that the LAS data is affected by the small amount of pyrite by pulling the data to the right (high Umaa value due to the high number of electrons associated with pyrite) and the gas by pulling the data above the lithologic triangle (low RHOma due to the low density of gas).

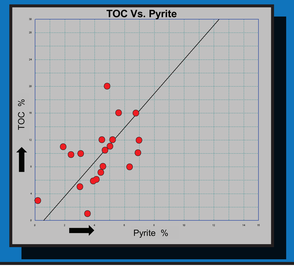
# CORE AND WELLLOG ANALYSIS



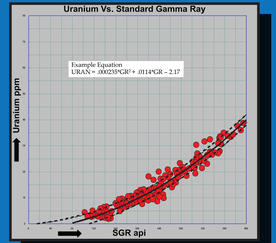

Logarithmic plot of the Total Organic Carbon (TOC) Vs. the Uranium (U). This plot illustrates a logarithmic relationship between the measured TOC and the U curve. As TOC increases logarithmically, U increases.




Plot of the Total Organic Carbon (TOC) Vs. the Bulk Density (RHOB). This plot illustrates a linear relationship between the measured TOC and the density curve in the well log. As TOC increases, RHOB decreases.

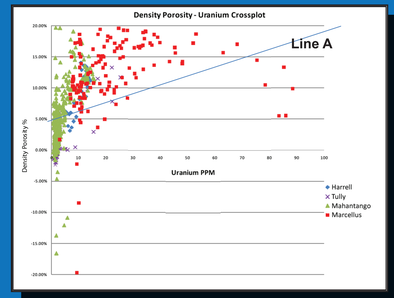



Plot of the amount of Total Organic Carbon (TOC) Vs. the amount of pyrite in the Marcellus Shale. The plot above illustrates with an increase in the amount of TOC, there is an increase in the percent of pyrite. This relationship and the results from the RHOma-Umaa plot would suggest the TOC and, consequently, gas is affecting the Bulk Density tool more than the presence of pyrite.

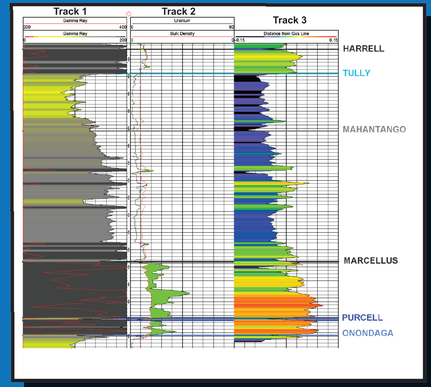



Plot of the Standard Gamma Ray (SGR) Vs. the Uranium (U). Because U is tied to the amount of TOC in the Marcellus as well as the gas, it is an important curve when attempting to model and prospect the shale. When not available, the U curve can be generated from the SGR.

# GAS IDENTIFICATION




Above, a relationship is recognized between the gamma ray and density porosity, specifically the Uranium (U) in the Spectral Gamma Ray tool. An increase in U correlates to an increase in TOC. The relationship between the U and density porosity shows anything above this line (Line A) can be considered gas-rich. The Marcellus has a large amount of gas and high TOC whereas the Mahantango and Harrell do not have high TOC values, but they do have a noticeable amount of gas. Above and to the right, a log expresses the relationship from the Uranium-Density cross plot. In Track 2, when the U value exceeds the bulk density value, it is highlighted in green. These highlighted areas have high potential for free and bound gas. Track 3 is an attempt to assign a value to an area in the Marcellus by measuring the distance above Line A. The warmer colors (green-red) represent values above Line A. This is calculated by using the Point-To-Line Theorem which measures the distance from any point in space tangent to a line. Equation 1 is the equation of Line A which must then be put into the correct form illustrated by Equation 2. Once put into this form, the variables must be put into Equation 3 to solve for the distance away from the line. Both methods (Tracks 2 & 3) appear to correlate to gas rich zones; however, the method in Track 3 has potential to identify zones with the highest amount of gas in place.




Equation 1

B*PHID = A*Uran + C

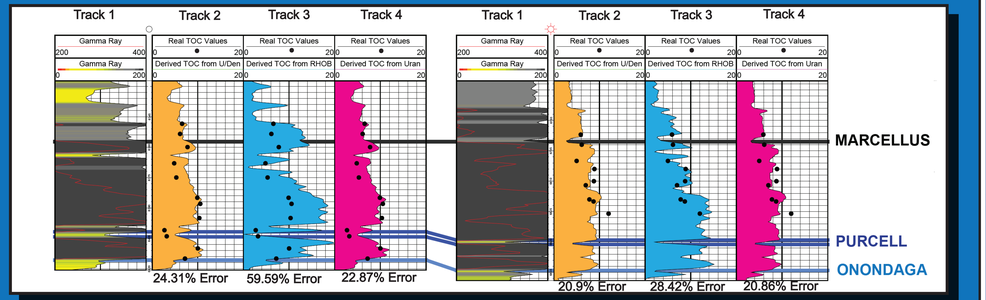
Equation 2

B*PHID - A*Uran - C = 0

Equation 3

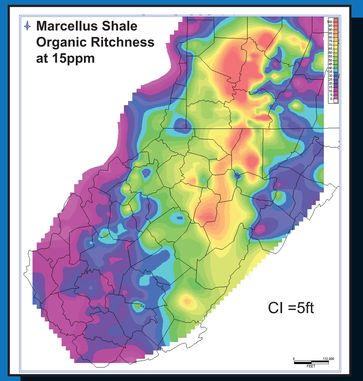
$$D = \frac{(A*Uran + PHID*B + C)}{\sqrt{(A^2 + B^2)}}$$

# PREDICTION OF TOTAL ORGANIC CARBON

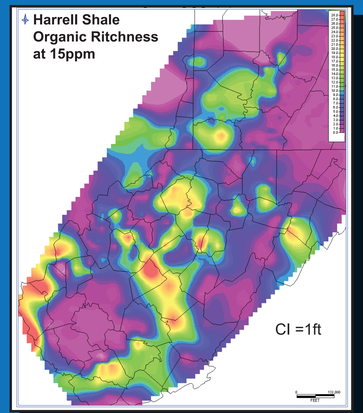



Above are two example wells with generated TOC curves for the Marcellus. There has been an established relationship between the measured amount of Total Organic Carbon (TOC) in the rock data to the bulk density (RHOB) and Uranium (U) log data. Also, it has been noted with an increase in TOC there is an increase in gas in the Marcellus. Because of these relationships, curves can be generated to predict the amount of TOC in the Marcellus. Three methods were attempted to accurately predict the amount of TOC. The most common method is using a linear regression of the RHOB Vs. TOC (Track 3). This method is the most sensitive and works well but only when one has a large amount of TOC rock data. The next method attempted was a logarithmic regression of the U vs. TOC relationship (Track 4). The U tool is less sensitive than the RHOB but it is not affected by washout and will give more conservative results on average. Also, it is much more accurate than the linear regression of RHOB (Track 3) when little TOC data is available to calibrate the curve. The last method was a logarithmic regression of the RHOB/U ratio (Track 2). This method attempted to take into account the sensitivity of the RHOB tool with the more conservative estimates of the U tool. The results from the percent error indicates when little TOC data is available to calibrate the curve, using the U and RHOB/U ratio logarithmic regressions are more accurate than a linear regression of the RHOB tool.

# ORGANIC RICHNESS MAPS

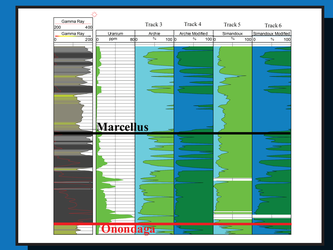



Map of the Marcellus Shale Organic Richness at 15 ppm from the Uranium curve. The warm colors represent the thick values and the cooler colors are thin. Anything above 15 ppm has correlated to gas rich zones and is more likely to have a large amount of TOC. On this map, there is a clear trend of organic rich areas trending approximately NW-SE. This represents the shelf break, area B, as noted on the isopachs and depositional models. This area was a paleo-low that allowed for more accumulation of TOC.




Map of the Harrell Shale Organic Richness at 15 ppm from the Uranium curve. The warm colors represent the thick values and the cooler colors are thin. Anything above 15 ppm has correlated to gas rich zones and is more likely to have a large amount of TOC. On this map, there are inconsistent areas of high amounts of TOC accumulation. The Harrell would have had more accumulation of TOC in the paleo-low areas as a result of the underlying deposition. Therefore, there would be more accumulation at the shelf breaks A and B, as shown on the previous maps and models.

# WATER SATURATION CALCULATIONS




Equation 1

$$S_w = \left(\frac{R_w * a}{\phi^m * Rt}\right)^{\frac{1}{n}}$$

Equation 2

$$S_{wu} = \left(\frac{R_w * a}{\phi^m * Rt * U_{log}}\right)^{\frac{1}{n}}$$

Equation 3

$$S_w = \frac{\sqrt{\left(\frac{V_{sh}}{R_{sh}}\right)^2 + 4\cdot\left(\frac{\phi^m}{a*R_w*(1-V_{sh})}\right)\cdot\frac{1}{R_t}} - \frac{V_{sh}}{R_{sh}}}{2\cdot\left(\frac{\phi^m}{a*R_w*(1-V_{sh})}\right)} \Rightarrow V_{sh} \text{ OR } \frac{\text{Vsand}}{\text{Shale Sand}}$$

Equation 4

$$S_{wu} = \frac{\sqrt{\left(\frac{U_{sh}}{R_{sh}}\right)^2 + 4\cdot\left(\frac{\phi^m}{a*R_w*(1-V_{sh})}\right)\cdot\frac{1}{R_t}} - \frac{U_{sh}}{R_{sh}}}{2\cdot\left(\frac{\phi^m}{a*R_w*(1-V_{sh})}\right)} \Rightarrow V_{sh} = \frac{U_{log} - U_{ma}}{U_{sh} - U_{ma}}$$

The Uranium (U) content can be incorporated into water saturation calculations. The water saturation for the Marcellus is typically calculated by using the Archie equation (Equation 1) or the Simandoux shale correction for the Archie equation (Equation 3). The Archie equation is a more conservative equation that was originally derived to be used in sandstones. The equation does not take into account shale particles that suppress resistivity or the measured tortuosity of shale. Archie overestimates water saturations in shale and since Uranium is directly tied to gas and TOC content (Track 3), it can be incorporated into the Archie equation as seen in Equation 2 (Track 4). Another equation used is the Simandoux shale correction for Archie. The Simandoux equation was derived specifically for sandy-shaly units to compensate for bound water by using a Vshale ratio from the gamma ray tool. When the Simandoux correction is applied to shale, it overestimates gas content (Track 5). Considering the Uranium is tied to the gas in shale the Vuran ratio was substituted for a Vshale ratio (Equation 4). The Vuran ratio is calculated by subtracting the shale value minus the U divided by the shale minus the sand. The change of this ratio helps to identify areas in the shale that will have a higher potential for free and bound gas (Track 6).

# CONCLUSIONS

- Marcellus Shale is defined in the subsurface by exceeding 200 API and a bulk density of less than 2.55 g/cc.
- For a shale, the Marcellus has a relatively high percentage of quartz.
- Pyrite and gas influence the lithologic analysis of the Marcellus.
- Gas can be correlated to higher Uranium and TOC values.
- Gas potential exists in the Marcellus, Mahantango, and Harrell shale units that can be identified in a log when the Uranium exceeds the bulk density or by measuring the distance from the line in the Uranium-Bulk Density cross-plot.
- TOC curves can be accurately generated from logarithmic regressions of the Uranium curve and the Density/Uranium ratio.
- A modified Archie and Simandoux equation using Uranium content predicts a more accurate value for water and gas saturations.
- Offshore eperic sea environment
- Limestone and black shale are equivalent facies.
- Shelf breaks at A and B have a higher regional accumulation of TOC.
- Localized highs and lows in the Onondaga control thickness and TOC accumulation of the Marcellus.

# ACKNOWLEDGEMENTS

I would first like to thank my advisor Dr. Tim Carr for working with me on this project and helping anytime I had a question. I would also like to thank the DOE and NETL for funding this project and providing me with the tools to complete this study. Next I would like to thank Dominion Exploration and Production and EQT for contributing data to this project. Without this contribution the study would have not been able to get off the ground. Lastly I would like to thank my friends and the rest of the faculty at WVU.